The spatial-temporal characteristics and health impacts of ambient fine particulate matter in China

Yingshi Song^a, Xiaoke Wang^a, Barbara A. Maher^b, Feng Li^{a,*}, Chongqi Xu^a,
Xusheng Liu^c, Xiao Sun^a, Zeyang Zhang^a

^a State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 18 Shuangqing Road, Haidian District, Beijing, 100085, China

^b Centre for Environmental Magnetism & Palaeomagnetism, Lancaster Environment Centre, Lancaster University, Lancaster, La1 4YQ, United Kingdom

^c Chinese Academy of Forest Inventory and Planning, State Forestry Administration, 18 Hepingli East Street, Beijing, 100714, China

ARTICLE INFO

Article history:

Received 29 November 2014

Received in revised form

1 May 2015

Accepted 2 May 2015

Available online 9 May 2015

Keywords:

Air pollution

Fine particulate matter

Health impact

China

ABSTRACT

Airborne particulate matter presents a serious health threat to human beings, but in China there have until now been few epidemiological studies, especially regarding the impact of ambient fine particulate matter (PM_{2.5}). This study explored first the temporal and spatial characteristics of ambient airborne PM_{2.5} in China, 2013. Mortality, respiratory diseases, cardiovascular diseases, and chronic bronchitis were then evaluated as four health endpoints attributable to PM_{2.5}. The results showed that the average annual PM_{2.5} concentration was 72.71 µg/m³; the PM_{2.5} concentration was below 35 µg/m³ for only 6% of the time, for the whole year. In terms of the PM_{2.5} concentration, January (133.10 µg/m³) and December (120.19 µg/m³) were the most polluted months, whereas July (38.76 µg/m³) and August (41.31 µg/m³) were the least polluted months. The most highly polluted areas were concentrated in North China. In terms of the health endpoints attributable to PM_{2.5}, there were 763,595 mortality, 149,754 cardiovascular diseases, 446,035 respiratory diseases, and 2,389,035 chronic bronchitis cases. Results were very important to clarify the current PM_{2.5} pollution situation and the health impact of PM_{2.5} in China. And also provided a reference for the assessing damage caused by PM_{2.5} pollution.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Air pollution is a major problem in many big cities all over the world (Yuan et al., 2012; Wang et al., 2013a; Yang et al., 2015), especially in developing countries (Zhang et al., 2013; Chen et al., 2014). Human exposure to high levels of airborne particulate matter (PM) can reduce projected life expectancies by between 1 year (WHO, 2003) and 5.5 years (Chen et al., 2013). Fine particulate matter (PM_{2.5}) with a diameter less than 2.5 µm has serious adverse effects on human health (Kampa and Castanas, 2008; Dockery and Pope, 1994; Zhang et al., 2012). Because of its small particle size, PM_{2.5} can reach the lungs and alveolar regions (Kampa and Castanas, 2008), and ultrafine particles (<0.1 µm) can enter the

blood vessels (Nemmar et al., 2002). Previous studies showed that there are positive and statistically significant relationships between short-term exposure to PM_{2.5} and cardiovascular and respiratory diseases (Ostro, 2004; Pascal et al., 2014). Moreover, research has shown that there are long-term effects of PM_{2.5} pollution on mortality (Giannadaki et al., 2014; Weichenthal et al., 2014).

In many cities in China, the air quality is poor. According to 2005 data, only 1% of Chinese citizens live in cities where the annual average concentration of PM₁₀ (particulate matter with diameter less than 10 µm) is less than 40 µg/m³ (World Bank, 2007). According to Aaron et al. (2010), the annual average concentration of PM_{2.5} in eastern China in 2010 was more than 80 µg/m³. China has the largest population in the world (1.36 billion by the end of 2013). There were some studies which have examined the health effects of PM pollution in China (e.g. Chen et al., 2011; Anderson et al., 2012; Chen et al., 2012). Some of these studies have researched the health impacts of PM₁₀ (Chen and Kan, 2008; Chen et al., 2011; Jahn et al., 2011). And some researches focus on the health impacts of PM_{2.5} (Cheng et al., 2013; Lee et al., 2012; Turner et al., 2011). But studies based on real-time monitoring data of the whole country were few.

* Corresponding author. Tel.: +86 10 62849103.

E-mail addresses: keystone2006@163.com (Y. Song), wangxk@rcees.ac.cn (X. Wang), b.maher@lancaster.ac.uk (B.A. Maher), lifeng@rcees.ac.cn (F. Li), 1158589370@qq.com (C. Xu), liuxush@163.com (X. Liu), sxdreamfree@163.com (X. Sun), 363249849@qq.com (Z. Zhang).

So our study was important to accessing pollution situation of PM_{2.5} in China and the health damage caused by PM_{2.5} in China.

2. Literature review

2.1. The data sources

The data sources of some studies about the health impacts of PM, were either from satellite-based remote sensing or recalculated from the air pollution index. Aaron et al. (2010) produced a global PM_{2.5} distribution based on satellite imagine. Yao and Lu (2014), estimated the spatiotemporal distribution of PM_{2.5} over China by satellite remote sensing. Qu et al. (2010) and Cheng et al. (2013) recalculated the concentration of PM_{2.5} from the air pollution index (API). But the studies based on real time date were few. Until 2012, 74 cities in China's national monitoring network have released PM_{2.5} data in real-time, and at the beginning of 2013, the number of cities releasing PM_{2.5} data reached 113, and at the end of 2013, 190 cities were releasing PM_{2.5} data. We selected 463 monitoring stations to conduct our research. These stations were located in all over the country of China.

2.2. The health impact assessment

The Health impact assessment (HIA) was widely used in air pollution hazard. Huang and Zhang (2013) evaluated the health benefit from PM_{2.5} pollution controlling in the region of Beijing-Tianjin-Hebei province. Dias et al. (2012) assessed the particulate matter and health risk in Portugal. Matus et al. (2012) used this model to estimate the health damages in China attributed to air pollution. We quantitatively assessed the health impact of airborne PM_{2.5} by exposure–response functions, as described by Cheng et al. (2013) and the World Bank (2007).

The aims of this study were first to explore the spatial-temporal characteristics of PM_{2.5} concentrations in Chinese cities, and then, in combination with population data, to estimate the health impacts of airborne PM_{2.5} exposure.

3. Data and methods

3.1. Source of PM_{2.5} data

We collected the 347-day dataset from January 18, 2013 to December 31, 2013 for use as experimental data, from the National Urban Air Quality Real-time Publishing Platform (<http://113.108.142.147:20035/emcpublish/>). These data were measured by 463 monitoring stations, which were distributed throughout the country of China. Each monitoring station automatically measured hourly PM_{2.5} concentration of the air. Each city has at least four air quality monitoring stations, which are distributed from the suburbs to downtown. Big cities, like Beijing, have 12 monitoring stations. The annual average of PM_{2.5} concentration of each monitoring station was calculated based on the hourly real-time data. As the original PM_{2.5} concentration data were at discrete points, Ordinary Kriging method was used to interpolate the site data into surface data to characterize concentrations over the entire area of each city. Then we got the annual average concentration of PM_{2.5} in each city or county-level city of China. The unit of concentration is $\mu\text{g}/\text{m}^3$.

3.2. Census data

The population data were from the Sixth National Population Census of the People's Republic of China, 2010. The population data includes the permanent resident population of the city, but does not include data on temporary residents. According to the Sixth

National Population Census of the People's Republic of China, 2010, the population of China was 1.36 billion, and which located in 2690 cities or county-level cities of China in our study.

3.3. Health impact assessment

The basic assumption of Health impact assessment (HIA) method is that, if the pollutant concentration exceeds the safe threshold, we can calculate the risk by $1 \mu\text{g}/\text{m}^3$ increment based on an epidemiological coefficient for one person. If we know the population of one city, we can estimate the health impact for the whole city.

Four health endpoints associated with PM_{2.5} were examined in this study: mortality, respiratory diseases, cardiovascular diseases, and chronic bronchitis.

The relative risk (RR) for the health outcomes was calculated using Equation (1):

$$RR = \exp[\beta^*(C - C_0)] \quad (1)$$

Where C is the annual average PM_{2.5} concentration, and C_0 is the reference PM_{2.5} concentration. Here, we applied a value of $10 \mu\text{g}/\text{m}^3$ for C_0 because according to the WHO (2005), an average annual PM_{2.5} concentration less than $10 \mu\text{g}/\text{m}^3$ is considered safe. The β is the empirical coefficient, i.e., the percentage increase in health effect per $1 \mu\text{m}/\text{m}^3$ PM_{2.5} increment. The β values for the four endpoints are listed in Table 1.

The number of cases for each health endpoint attributed to PM_{2.5} (E) is calculated by multiplying the population (P) by the difference in the current incident rate (f_p) and the incidence rate in a clean environment (f_0), as shown in Equation (2).

$$E = P * (f_p - f_0) \quad (2)$$

The current incident rate (f_p) is calculated by multiplying the incidence rate in a clean environment (f_0) by the relative risk (RR), as shown in Equation (3).

$$f_p = f_0 * RR \quad (3)$$

By substituting Equation (3) into Equation (2), we obtain E .

$$E = ((RR - 1) / RR) * f_p * P \quad (4)$$

The f_p values for the four endpoints are listed in Table 1.

4. Results

4.1. Annual and seasonal variation of PM_{2.5}

The annual average PM_{2.5} concentration in all cities was $72.71 \mu\text{g}/\text{m}^3$. The hourly variation of PM_{2.5} concentrations in China (Fig. 1) showed that for only 6% of the time was the PM_{2.5} concentration below $35 \mu\text{g}/\text{m}^3$ (Interim target-1 of WHO, 2005). For more than half of the time during the whole year, the PM_{2.5} concentration was between $35 \mu\text{g}/\text{m}^3$ and $75 \mu\text{g}/\text{m}^3$. The rest of the time (37% of the year), the airborne PM_{2.5} concentrations were over $75 \mu\text{g}/\text{m}^3$. During December, there were two episodes when the average PM_{2.5} concentration of all cities reached $215 \mu\text{g}/\text{m}^3$, which is more than five times higher than the reference value ($35 \mu\text{g}/\text{m}^3$). January ($133.10 \mu\text{g}/\text{m}^3$) and December ($120.19 \mu\text{g}/\text{m}^3$) were the months with the most pollution, while July ($38.76 \mu\text{g}/\text{m}^3$) and August ($41.31 \mu\text{g}/\text{m}^3$) had better air quality in China. The highest PM_{2.5} concentrations were recorded in the winter ($112.30 \mu\text{g}/\text{m}^3$), whereas the lowest PM_{2.5} concentrations were recorded in the summer ($44.63 \mu\text{g}/\text{m}^3$). In the spring and autumn, the average

Table 1

Concentration-response empirical coefficients and current incidence rates for the four health endpoints.

Health endpoints	Empirical coefficient β (95% confidence interval)	Current incident rate f_p	Reference ^a
Mortality	0.0336 (0.00076, 0.00504)	Mortality rates of each city	1, 3, 4, 5, 6, 7, 13, 14
Cardiovascular diseases	0.00068 (0.00043, 0.00093)	0.00546	2, 4, 5, 6, 7, 13
Respiratory diseases	0.00109 (0, 0.00221)	0.01022	2, 4, 5, 6, 7, 8, 13
Chronic bronchitis	0.01009 (0.00366, 0.01559)	0.00694	4, 9, 10, 11, 12, 14

^a 1. Burnett et al., 2014; 2. Xie et al., 2009; 3. Huang and Zhang, 2013; 4. Aunan and Pan, 2004; 5. Jin et al., 1999; 6. Xu et al., 2000; 7. Kan and Chen, 2003; 8. Wong et al., 2001; 9. Zhang et al., 1999; 10. Xu and Wang, 1993; 11. Jin et al., 2000; 12. Xiao et al., 1990; 13. Xie et al., 2010; 14. Kan and Chen, 2002.

Fig. 1. Hourly variation of the PM_{2.5} concentration in China during 2013.

values were 62.27 $\mu\text{g}/\text{m}^3$ and 68.82 $\mu\text{g}/\text{m}^3$, respectively. The concentration of PM_{2.5} in the winter was approximately 2 $\times$ higher than in the summer (Fig. 2).

4.2. The spatial distribution of PM_{2.5}

According to the WHO (2005), the safe threshold value of PM_{2.5} is 10 $\mu\text{g}/\text{m}^3$ (annual average). Only 32 cities in our study met this standard, which were located in Southeast and Southwest China. The cities with the cleanest air always located in the South China Sea coastal region, or the northwestern tableland, where has few pollution sources. Areas experiencing the highest airborne PM_{2.5} levels were concentrated in North China, Northeast China, and Northwest China (Fig. 3). There were 12 cities with annual PM_{2.5} concentrations above 100 $\mu\text{g}/\text{m}^3$ in China, and the top ten were Shijiazhuang (145.19 $\mu\text{g}/\text{m}^3$), Xingtai (137.94 $\mu\text{g}/\text{m}^3$), Handan (133.88 $\mu\text{g}/\text{m}^3$), Ji'ning (129.81 $\mu\text{g}/\text{m}^3$), Baoding (127.91 $\mu\text{g}/\text{m}^3$), Hengshui (119.77 $\mu\text{g}/\text{m}^3$), Langfang (118.59 $\mu\text{g}/\text{m}^3$), Tangshan (117.81 $\mu\text{g}/\text{m}^3$), Tai'an (117.32 $\mu\text{g}/\text{m}^3$), and Jinan (112.86 $\mu\text{g}/\text{m}^3$). These cities are located in the Hebei Province and in the Shandong Province. The annual average PM_{2.5} concentration of these ten cities was 126.11 $\mu\text{g}/\text{m}^3$, which was 53.28 $\mu\text{g}/\text{m}^3$ higher than the average of all of the 86 cities in this study and 91.11 $\mu\text{g}/\text{m}^3$ higher than the Chinese safe standard (GB 3095-2012), and 116 $\mu\text{g}/\text{m}^3$ than WHO (2005) safe standard.

Fig. 2. Seasonal variation of PM_{2.5} concentration in China during 2013.

4.3. Health impact due to PM_{2.5} levels

There were 32 cities met the WHO (2005) air quality standard (with the concentration of PM_{2.5} less than 10 $\mu\text{g}/\text{m}^3$), they were Lhasa, Cuomei, Luozha, et al. We exclude them from comparison

Fig. 3. PM_{2.5} concentrations of China during 2013.

with the remaining 2824 polluted cities, for our investigation of health impacts. The four health endpoints associated with $PM_{2.5}$ are shown in Fig. 4. The total number of premature deaths attributable to $PM_{2.5}$ was 763,595 for all of the cities. Daqing, a city of Heilongjiang Province, Shenyang, and Beijing had the highest risk attributable to $PM_{2.5}$, with 3849, 3352, 3260 deaths respectively. There were two reasons for the high number of deaths, one was the high $PM_{2.5}$ concentration, and the other was high population. In contrast, Jiangda, a city of Tibet in had only 1 deaths attributable to

the $PM_{2.5}$ in 2013, because Jiangda It had a low $PM_{2.5}$ concentration ($24.17 \mu\text{g}/\text{m}^3$), even has a population of 3755.

The numbers of cardiovascular and respiratory diseases were 149,754 and 446,035, respectively. The North China, Central China, Northeast, and coastal areas of Bohai Sea and Yellow Sea of China were the most affected regions. The south and southeast regions of China, including Fujian, Guangdong, Guangxi, Yunnan, and Haikou Province had few cardiovascular and respiratory diseases caused by $PM_{2.5}$. The most serious city was Beijing with 1045 cardiovascular

Fig. 4. The number of cases attributable to $PM_{2.5}$ for four health endpoints in China. (A) Mortality caused by $PM_{2.5}$; the (B) respiratory diseases caused by $PM_{2.5}$; (C) cardiovascular diseases caused by $PM_{2.5}$; (D) chronic bronchitis caused by $PM_{2.5}$.

diseases and 3109 respiratory diseases caused by PM_{2.5}. While Tibet was the suffered the least.

There were 2.39 million people affected with chronic bronchitis attributed to PM_{2.5}. The area affected was wide, the North China, the Yangtze River Delta, and Xinjiang province were the three most severely afflicted areas. Other cities including Ha'erbin, Shenyang, Changchun, Chengdu, Chongqing, Xi'an, Wuhan, and Changsha also had high numbers of chronic bronchitis cases. Beijing was the most seriously affected city, with 16,295 chronic bronchitis cases attributed to PM_{2.5}, accounting for 0.24% of the total population of Beijing.

4.4. Sensitivity analysis and uncertainty analysis

Substantial uncertainty may be involved in the HIA, because exposure-response relationships may differ by different places and different time. In this section, we conduct a sensitivity analysis with regard to exposure-response functions by using upper and lower bound values of exposure-response functions acquired from the 5% changes of PM_{2.5} concentration. We compare simulation results based on upper and lower bound exposure-response values with those based on central exposure-response values. The sensitivity analysis results (Table 2) showed that the four health endpoints outcomes were highly sensitive to exposure-response functions. The 95% confidence interval of mortality, cardiovascular diseases, respiratory diseases, and chronic bronchitis were, (739,532–787,574), (144,820–154,680), (431,448–460,608), and (2,321,505–2,455,851), respectively.

5. Discussion

5.1. Temporal characteristics of PM_{2.5} concentrations

The summer was the cleanest season, with a relatively low concentration of airborne PM_{2.5}, although there were several short-duration, e.g. in the 3rd, June; 16th, June; 17th June and 1st July. And it did not last long time, 2 h–5 h. The peak was relatively low, less than 80 µg/m³. And winter was the most polluted season. Similar conclusion was found by Yao and Lu (2014) studied in Jing-Jin-Ji, the concentrations of PM_{2.5} were high in winter, and the lowest level was measured in summer. Several reasons may account for this phenomenon. The first reason is related to the winter heating system; known as the Huai River Policy (Chen et al., 2013), the government supplies heat to homes and offices in most northern cities by burning coal during the winter. This method of heating produces abundant PM, especially PM_{2.5}. The heating period of Northeast were from November 1 to April 1 of next year, which lasts 5 months. This was the main reason that the concentration of PM_{2.5} in Northeast was high. Second, erosion and transport of soil- and desert-derived mineral dust occurs most efficiently during the late winter/early spring (e.g. Tan et al., 2012), related to surface northwesterly winds and dry conditions of the winter monsoon, and springtime development of frontal and convective weather systems (with some summertime dust events associated

with cyclone activity). Major mineral dust source areas include the Tarim Basin, the Hexi corridor and the Loess Plateau. A third reason for the observed seasonality may involve vegetation. Plant leaves play an important role in cleaning the air (Mitchell et al., 2010; Yin et al., 2011) and accumulating particles (Sternberg et al., 2010; Popek et al., 2013). North China has a temperate climate, and the leaves of deciduous species fall in the winter. During this season, deciduous plants are less able to accumulate airborne PM. Another reason involves meteorology. The concentration of PM_{2.5} is negatively related to rainfall (Tiwari et al., 2012). In most Chinese cities, precipitation is highest in the summer monsoon, and this rainfall leads to a low PM_{2.5} in the summer.

5.2. The driving forces for PM_{2.5} pollution

Spatially, the PM_{2.5} concentrations in China were higher in the east than in the west, and higher in the north than in the south. The most highly polluted areas were North China and Central China. Some studies have indicated that economic and population growth, and urbanization were the main driving forces for PM production (Tang, 2004; Chen and Kan, 2008; Linet al., 2013). In our research, the most populated regions are rapidly developing economic zones and densely populated areas. The gross domestic product (GDP) of these three areas accounts for 43% of the national Chinese GDP, and the population of these three regions accounts for 27% of the total Chinese population (National Bureau of Statistics of China, 2010). The highest population exposure to PM_{2.5} was in Chongqing city, followed by Beijing, Shijiazhuang, and Shanghai. According to Yao and Lu (2014), Shanghai had the highest population exposure in 2010, followed by Beijing and Tianjing, as measured by the remote-sensing method. The highest PM_{2.5} production per unit GDP was in Tongchuan, a city in the Shaanxi Province.

5.3. The health impacts due to PM_{2.5}

Studies have examined the health effects of PM_{2.5} (Hu et al., 2012; Huang et al., 2012; Yang et al., 2012; Hu et al., 2014), but these previous investigations studied either a single city or a single health impact indicator. In our study, we examined four health endpoints: premature mortality, respiratory diseases, cardiovascular diseases, and chronic bronchitis. We find that 763,595 deaths were attributable to PM_{2.5} in China, during 2013, which is 0.056% of the whole Chinese population. A study by Wang et al. (2013b) in China reported that there were 1.25 million premature deaths attributable to air pollution. This number may include other types of air pollution, such as O₃ and NO_x. Cao et al. (2012) performed a study from 2004 to 2008 and reported that there were 26.2 non-accidental deaths per day in the city of Xi'an because of cardiovascular diseases and respiratory diseases. In our study, the number of premature deaths in Xi'an was 30.46, approximately 4 more persons per day. Of the endpoints attributed to PM_{2.5}, the largest number comprised the bronchitis cases. There were 2.39 million bronchitis cases in all of the cities studied, accounting for 0.17% of all Chinese. Therefore, if the PM_{2.5} levels were controlled and if a safe concentration was established, a substantial number of deaths and diseases would be avoided.

5.4. The way forward for China

Some measures can be taken to control pollution sources, (1) Changes in the structure of energy consumption. According to EIA (2014), coal consumption accounted for 69% of the total energy consumption, 18% from oil (in 2011) and compared to less than 8% from hydroelectric and nuclear sources in China. The main sources of PM_{2.5} in China are anthropogenic sources, including coal

Table 2
Sensitivity analysis, lower and upper bound values of exposure-response functions by the changes of PM_{2.5} concentration (5%).

Health endpoints	Lower-bound		Upper-bound	
	Cases	%	Cases	%
Mortality	715,375	6.31%	811,467	6.27%
Cardiovascular diseases	139,887	6.59%	159,605	6.58%
Respiratory diseases	416,838	6.55%	475,163	6.53%
Chronic bronchitis	2,253,228	5.68%	2,521,940	5.56%

emissions and vehicle emissions (Li et al., 2012). So changing currently energy consumption structure are badly needed. (2) Improvement of the existing equipment, and reduce the emissions. The air quality of EU improved significantly when they finished equipment up-grading (Zhu et al., 2013). (3) To improve the traffic and control the car number. In Japan, by adopting strict traffic management, the annual average concentrations of PM_{2.5} reduced 49.8% (Hara et al., 2013). (4) Set laws and regulations. The U.S. environmental protection agency (USEPA) have improved the air quality by the implementation of the clean air interstate regulations (CAIR), Clean air visibility rules (CAVR) and a series of cuts. China has realized that it is an extremely urgent issue to control air pollution, and is implementing mitigation measures (Zhu et al., 2013). In 2011, China released the air quality monitoring schedule; in 2012, China introduced new national air quality standards (GB3095-2012); in 2013, the State Council of China determined 10 measurements to prevent and control atmospheric pollution. Perhaps, only if China conducts an energy transition, uses more clean energy and/or improves combustion technologies, can the ongoing problem of urban air quality be resolved. The Chinese government aims to have an annual average PM_{2.5} concentration of less than 35 µg/m³ nationally by the beginning of 2016 (Yuan et al., 2012). Therefore, mitigating airborne PM_{2.5} concentration remains a very difficult challenge.

6. Conclusions

We found that during 2013, the annual average of PM_{2.5} concentration was 72.71 µg/m³ in China. The highest PM_{2.5} concentrations were recorded in winter (112.30 µg/m³), whereas the cleanest season was summer (44.63 µg/m³). The most highly polluted areas were concentrated in North China. In terms of the health impacts, there were 763,595 deaths, 149,754 cardiovascular diseases, 446,035 respiratory diseases, and 2,389,036 chronic bronchitis cases caused by PM_{2.5}.

Acknowledgements

This research was supported by the China Forestry Nonprofit Industry Scientific Research Special Project (Grant No. 201304301); National Science Foundation of China (No. 41030744, 71273254).

References

- Aaron, V.D., Martin, R.V., Brauer, M., 2010. Global estimates of ambient fine particulate matter concentrations from satellite-based aerosol optical depth: development and application. *Environ. Health Perspect.* 118, 847.
- Anderson, J.O., Thundiyil, J.G., Stolbach, A., 2012. Clearing the air: a review of the effects of particulate matter air pollution on human health. *J. Med. Toxic.* 8, 166–175.
- Aunan, K., Pan, X.C., 2004. Exposure-response functions for health effects of ambient air pollution applicable for China – a meta-analysis. *Sci. Total Environ.* 329, 3–16.
- Burnett, R.T., Pope, C.A., Ezzati, M., Olives, C., et al., 2014. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environ. Health Perspect.* 122, 397–403.
- Cao, J., Xu, H., Xu, Q., Chen, B., Kan, H., 2012. Fine particulate matter constituents and cardiopulmonary mortality in a heavily polluted Chinese city. *Environ. Health Perspect.* 120, 373–378.
- Chen, B., Kan, H., 2008. Air pollution and population health: a global challenge. *Environ. Health Perspect.* 116, 94–101.
- Chen, R., Li, Y., Ma, Y., Pan, G.W., Zeng, G., Xu, X.H., Chen, B.H., Kan, H.D., 2011. Coarse particles and mortality in three Chinese cities: the China Air Pollution and Health Effects Study (CAPES). *Sci. Total Environ.* 409, 4934–4938.
- Chen, R., Huang, W., Wong, C.M., Wang, Z.S., Thach, T.Q., Chen, B.C., Kan, H.D., 2012. Short-term exposure to sulfur dioxide and daily mortality in 17 Chinese cities: the China air pollution and health effects study (CAPES). *Environ. Res.* 118, 101–106.
- Chen, Y., Ebenstein, A., Greenstone, M., Li, H., 2013. Evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River policy. *P. Natl. Acad. Sci.* 110, 12936–12941.
- Chen, Y., Schleicher, N., Chen, Y., Chai, F., Norra, S., 2014. The influence of governmental mitigation measures on contamination characteristics of PM_{2.5} in Beijing. *Sci. Total Environ.* 490, 647–658.
- Cheng, Z., Jiang, J., Fajardo, O., Wang, S., Hao, J., 2013. Characteristics and health impacts of particulate matter pollution in China (2001–2011). *Atmos. Environ.* 65, 186–194.
- Dias, D., Tchepe, O., Carvalho, A., Miranda, A.L., Borrego, C., 2012. Particulate matter and health risk under changing climate: assessment for Portugal. *Sci. World J.* 2012, 1–10.
- Dokery, D.W., Pope, C.A., 1994. Acute respiratory effects of particulate air pollution. *Ann. Rev. Public Health* 15, 107–132.
- EIA U.S., 2014. Energy Information Administration Report.
- Giannadaki, D., Pozzer, A., Lelieveld, J., 2014. Modeled global effects of airborne desert dust on air quality and premature mortality. *Atmos. Chem. Phys.* 14, 957–968.
- Hara, K., Homma, J., Tamura, K., et al., 2013. Decreasing trends of suspended particulate matter and PM_{2.5} concentrations in Tokyo during 1990–2010. *J. Air & Waste Manag. Assoc.* 63 (6), 737–748.
- Hu, X., Zhang, Y., Ding, Z., 2012. Bioaccessibility and health risk of arsenic and heavy metals (Cd, Co, Cr, Cu, Ni, Pb, Zn and Mn) in TSP and PM_{2.5} in Nanjing, China. *Atmos. Environ.* 57, 146–152.
- Hu, W., Downward, G.S., Reiss, B., 2014. Personal and indoor PM_{2.5} exposure from burning solid fuels in vented and unvented stoves in a rural region of China with a high incidence of lung cancer. *Environ. Sci. Technol.* 48, 8456–8464.
- Huang, D.S., Zhang, X.Q., 2013. Health benefit evaluation for PM_{2.5} pollution control in Beijing-Tianjin-Hebei region of China. *China Environ. Sci.* 33 (1), 166–174.
- Huang, W., Cao, J., Tao, Y., 2012. Seasonal variation of chemical species associated with short-term mortality effects of PM_{2.5} in Xi'an, a central city in China. *Am. J. Epidemiol.* <http://dx.doi.org/10.1093/aje/kwr342>.
- Jahn, H.J., Schneider, A., 2011. Particulate matter pollution in the megacities of the Pearl River Delta, China – a systematic literature review and health risk assessment. *Int. J. Hyg. Environ. Health* 214 (4), 281–295.
- Jin, L.B., et al., 1999. Association between air pollution and mortality in Benxi, China. *Chin. Pub. Health* 15 (3), 211–212 (in Chinese).
- Jin, L.B., Qin, Y., Xu, Z., 2000. Relationship between air pollution and acute and chronic respiratory disease in Benxi, China. *Chin. J. Environ. Health* 17 (5), 268–270 (in Chinese).
- Kampa, M., Castanas, E., 2008. Human health effects of air pollution. *Environ. Pollut.* 151, 362–367.
- Kan, H.D., Chen, B.H., 2002. Analysis of exposure response relationships of air particulate matter and adverse health outcomes in China. *J. Environ. Health* 19, 422–424.
- Kan, H.D., Chen, B.H., 2003. A case-crossover analysis of air pollution and daily mortality in Shanghai. *J. Occup. Health* 45 (2), 119–124.
- Lee, S.J., Serre, M.L., Van, D.A., 2012. Comparison of geostatistical interpolation and remote sensing techniques for estimating long-term exposure to ambient PM_{2.5} concentrations across the continental United States. *Environ. Health Persp.* 120, 1727–1732.
- Li, X., Liu, Z.R., Ren, X.Y., 2012. Characteristics of PM₁₀ and PM_{2.5} during summer time of 2007 and 2008 at Beijing National Stadium. *Trans. Atmos. Sci.* 35 (2), 197–204.
- Lin, G., Fu, J., Jiang, D., 2013. Spatio-temporal variation of PM_{2.5} concentrations and their relationship with geographic and socioeconomic factors in China. *Inter. J. Environ. Res. Pub. Health* 11, 173–186.
- Matus, K., Nam, K.M., Noelle, E.S., Lok, N.L., John, M.R., Sergey, P., 2012. Health damages from air pollution in China. *Glob. Environ. Chang.* 22, 55–66.
- Mitchell, R., Maher, B., Kinnersley, R., 2010. Rates of particulate pollution deposition onto leaf surfaces: temporal and inter-species magnetic analyses. *Environ. Pollut.* 158, 1472–1478.
- National Bureau of Statistics of China, 2010. <http://www.stats.gov.cn/english/>.
- Nemmar, A., Hoet, P.M., Vanquickenborne, B., Dinsdale, D., Thomeer, M., Hoylaerts, M., Vanbilloen, H., Mortelmans, L., Nemery, B., 2002. Passage of inhaled particles into the blood circulation in humans. *Circulation* 105, 411–414.
- Ostro, B., 2004. Outdoor Air Pollution. WHO Environmental Burden of Disease Series, No.5.
- Pascal, M., Falq, G., Wagner, V., 2014. Short-term impacts of particulate matter (PM₁₀, PM_{10-2.5}, PM_{2.5}) on mortality in nine French cities. *Atmos. Environ.* 95, 175–184.
- Popek, R., Gawrońska, H., Wrochna, M., Gawroński, S.W., Sæbø, A., 2013. Particulate matter on foliage of 13 woody species: deposition on surfaces and phytostabilisation in waxes: a 3-year study. *Int. J. Phytoremediat* 15, 245–256.
- Qu, W., Arimoto, R., Zhang, X., 2010. Spatial distribution and interannual variation of surface PM₁₀ concentrations over eighty-six Chinese cities. *Atmos. Chem. Phys.* 10, 5641–5662.
- Sternberg, T., Viles, H., Cathersides, A., Edwards, M., 2010. Dust particulate absorption by ivy *Hedera helix* on historic walls in urban environments. *Sci. Total Environ.* 409, 162–168.

- Tan, S.C., Shi, G.Y., Wang, H., 2012. Long-range transport of spring dust storms in Inner Mongolia and impact on the China seas. *Atmos. Environ.* 46, 299–308.
- Tang, X.Y., 2004. The Characteristics of Urban Air Pollution in China. National Academies Press.
- Tiwari, S., Chate, D., Srivastava, M., 2012. Statistical evaluation of PM₁₀ and distribution of PM₁, PM_{2.5}, and PM₁₀ in ambient air due to extreme fireworks episodes (Deepawali festivals) in megacity Delhi. *Nat. Hazards* 61, 521–531.
- Turner, M.C., Krewski, D., Pope III, C.A., Chen, Y., Gapstur, S.M., Thun, M.J., 2011. Long-term ambient fine particulate matter air pollution and lung cancer in a large cohort of never-smokers. *Am. J. Respir. Crit. Care Med.* 184 (12), 1374–1381.
- Wang, J.F., Hu, M.G., Xu, C.D., Christakos, G., Zhao, Y., 2013a. Estimation of citywide air pollution in Beijing. *PloS One* 8, e53400.
- Wang, H., Dwyer-Lindgren, L., Lofgren, K.T., 2013b. Age-specific and sex-specific mortality in 187 countries, 1970–2010: a systematic analysis for the global burden of disease study 2010. *Lancet* 380, 2071–2094.
- Weichenthal, S., Villeneuve, P.J., Burnett, R.T., 2014. Long-term exposure to Fine particulate matter: association with nonaccidental and cardiovascular mortality in the agricultural health study cohort. *Environ. Health Perspect.* 122, 609–615.
- WHO, 2003. Health Aspects of Air Pollution with Particulate Matter, Ozone and Nitrogen Dioxide. Report 2003 on a WHO Working Group. Bonn.
- WHO, 2005. Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen dioxide and Sulfur dioxide.
- Wong, C.M., Ma, S., Hedley, A.J., Lam, T.H., 2001. Effect of air pollution on daily mortality in Hong Kong. *Environ. Health Perspect.* 109 (4), 335–340.
- World Bank, 2007. Cost of Pollution in China: Economic Estimates of Physical Damages.
- Xiao, H.P., et al., 1990. Effects of air pollution on human respiratory disease in Shenyang. *Chin. J. Pub. Health* 6 (5), 195–198 (in Chinese).
- Xie, P., Liu, X.Y., Liu, Z.R., Li, T.T., Bai, Y.H., 2009. Exposure-response functions for health effects of ambient particulate matter pollution applicable for China. *China Environ. Sci.* 29 (10), 1034–1040.
- Xie, P., Liu, X.Y., Liu, Z.R., Li, T.T., Zhong, L.J., Xiang, Y.R., 2010. Impact of exposure to air pollutants on human health effects in Pearl River Delta. *China Environ. Sci.* 30 (7), 997–1003.
- Xu, X., Wang, L., 1993. Associations of indoor and outdoor particulate level with chronic respiratory illness. *Am. Rev. Respir. Dis.* 148, 1516–1522.
- Xu, Z., Yu, D., Jing, L., Xu, X., 2000. Air pollution and daily mortality in Shenyang, China. *Arch. Environ. Health* 55 (2), 115–120.
- Yang, S.Y., Chen, B., 2015. Trans-boundary total suspended particulate matter (TSPM) in urban ecosystems—a case study of Jing-Jin-Ji district. *Ecol. Model.* <http://dx.doi.org/10.1016/j.ecolmodel.2014.10.006>.
- Yang, C., Peng, X., Huang, W., 2012. A time-stratified case-crossover study of fine particulate matter air pollution and mortality in Guangzhou, China. *Int Arch Occup Environ Health* 85, 579–585.
- Yao, L., Lu, N., 2014. Spatiotemporal distribution and short-term trends of particulate matter concentration over China, 2006–2010. *Environ. Sci. Pollut. Res.* 21, 9665–9675.
- Yin, S., Shen, Z., Zhou, P., 2011. Quantifying air pollution attenuation within urban parks: an experimental approach in Shanghai, China. *Environ. Pollut.* 159, 2155–2163.
- Yuan, Y., Liu, S., Castro, R., Pan, X., 2012. PM_{2.5} monitoring and mitigation in the Cities of China. *Environ. Sci. Technol.* 46, 3627–3628.
- Zhang, J., Qian, Z., Kong, L., Zhou, L., Yan, L., Chapman, R.S., 1999. Effects of air pollution on respiratory health of adults in three Chinese cities. *Arch. Environ. Health* 54 (6), 373–382.
- Zhang, Y.J., Guo, Y.M., Li, G.X., Zhou, J., Jin, X.B., Wang, W.Y., Pan, X.C., 2012. The spatial characteristics of ambient particulate matter and daily mortality in urban area of Beijing China. *Sci. Total Environ.* 435–436, 14–20.
- Zhang, A., Qi, Q., Jiang, L., Zhou, F., Wang, J., 2013. Population exposure to PM_{2.5} in the urban area of Beijing. *PloS One* 8, e63486.
- Zhu, Z.Y., Li, B., Zhao, Q.Y., et al., 2013. A review and outlook of the research and pollution control on PM_{2.5} in domestic and overseas. *Environ. Sci. Technol.* 26 (01), 70–74 (in Chinese).